

Modeling of Growth Parameter Effects for Far-Infrared Blocked Impurity Band Detectors

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ABSTRACT

Numerical modeling has been performed as a function of compensation in the absorbing layer, net doping in the blocking layer and the extent of interface doping gradient at the absorber/blocker interface. Space charge effects cause field variations in the blocking layer at the net doping levels currently obtainable in development efforts for Ge and GaAs based BIBs. Increased space charge at the absorber/blocker interface creates a field gradient, leading to reduced net field in the blocker layer and an extension of the depletion region in the absorber.

INTRODUCTION

Blocked impurity band (BIB) detectors were developed to provide higher quantum efficiency, broader wavelength response and reduced sensitivity to ionizing radiation in comparison to conventional photoconductors¹. Large format arrays of Si:As and Si:Sb BIBs have become the detectors of choice for many applications in the $\sim 5\text{--}40\text{ }\mu\text{m}$ range^{2,3}. This wavelength coverage could be extended by the development of BIB devices using either Ge or GaAs as the host material. Since the problems of limited absorption, radiation sensitivity and transient response are even more pronounced for far-IR photoconductors, the extension of the BIB concept to longer wavelengths could have significant impact.

Efforts are underway to develop the epitaxial structures required for Ge and GaAs BIBs^{4,5}. Key challenges in both cases arise from the demands for 1) control of doping and very low compensation in the absorbing layer, 2) high purity epitaxy for the blocking layer and 3) the production of a sharp doping interface at the absorber/blocker interface. In both materials, the development of the material growth capability is closely coupled to the development of new detectors.

In this paper, we present numerical modeling of field profiles and responsivities for Ge:Ga BIB detectors, showing the effect of variations in doping levels and doping gradients. The numerical model extends earlier analytical modeling efforts⁶ by including the presence of space charge effects throughout the device, as well as both contacts. The model is a finite difference calculation in which the detailed balance, continuity and Poisson's equations are solved simultaneously in one dimension⁷. The BIB device is treated as a quasi ambipolar system, with free holes (+) / electrons (-) and ionized acceptors (-) / donors (+) respectively as mobile charge carriers.

The BIB device is modeled with four regions – a front contact, blocking layer, absorbing (active) layer and back contact. The absorbing layer is doped 2-3 orders of magnitude greater than a conventional photoconductor, while the high purity (blocking) layer blocks the hopping current that would otherwise flow through the more heavily doped material. In this model, hopping mobility in the absorber is treated following the approach of Petroff and Stapelbroeck⁸ for an idealized case where dopants are uniformly spaced. In the modeling to date, no mechanism is included for impact ionization effects, effectively limiting the gain to unity. This is a reasonable approximation when considering development of far-IR BIBs in Ge and GaAs, where the breakdown fields are relatively low. More details can be found in Ref. 7.

RESULTS

Electric Field Profiles for Si:Sb BIBs

The analytical model routinely applied to Si BIB detectors assumes negligible space charge and a constant field in the blocking layer, with a constant space charge depletion region in the absorbing layer. Figure 1 shows numerical simulation of the field profile in a Si:Sb detector as a function of bias, using doping and layer thickness parameters from Huffman et. al.³ The results show that the field in the blocking layer is, in fact, reasonably constant and the depletion region extends as expected into the absorber. In this simulation, we have assumed an ideally sharp doping interface between the absorbing and blocking layers.

Closer inspection of the field profile in the blocking layer shows that, in fact, there is a slight slope associated with a net space charge. This space charge arises from a difference between the concentration of the minority dopants and the concentration of ionized majority dopants. For the high purity levels attained in the Si devices (net doping $\sim 10^{12} \text{ cm}^{-3}$), these effects can be neglected. Similarly, the low degree of compensation in the absorber that can be achieved (2.5×10^{-5} for this example) means that the electric field can penetrate a significant distance at relatively low applied bias. We turn our attention now to modeling of BIBs for Ge:Ga growth parameters, beginning with compensation in the absorber, followed by net blocker doping and degree of interface gradient.

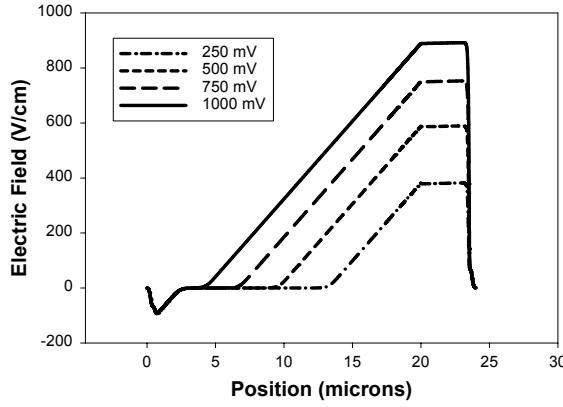


Figure 1: Field profiles for Si:Sb BIBs, with parameters taken from Ref. 3. The absorber/blocker interface is at 20 microns

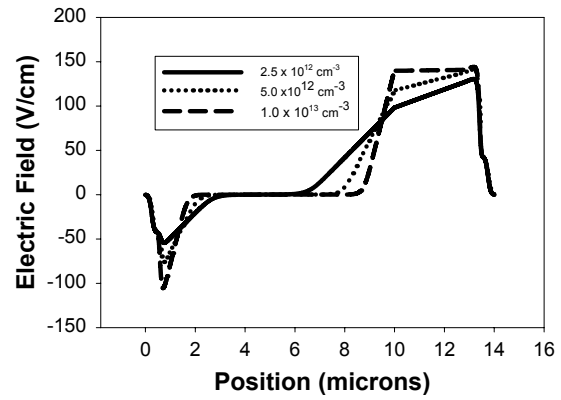


Figure 2: Field profiles for Ge:Ga BIBs as a function of compensation in the absorbing layer. Bias is 50 mV for all cases. Blocker doping is fixed.

Effect of Variation in Absorber Compensation

For the Ge:Ga BIB modeling, we have used a majority doping of $2 \times 10^{16} \text{ cm}^{-3}$ in the absorbing layer. Device thickness has been set at $14 \mu\text{m}$, with a $10 \mu\text{m}$ absorber and a $4 \mu\text{m}$ blocking layer. Figure 2 shows the effect of varying the minority doping (compensation) in the absorbing layer. For fixed bias one sees, as expected, an increase in depletion width with a decrease in compensation. This material variation in the absorbing layer also affects the field distribution in the blocking layer. This occurs because the space charge balance in the blocker is affected by the increased current and hole concentration associated with the increased depletion width. The field variations in the blocker, however, don't play a major role in the responsivity because the fields, though reduced in some cases, remain sufficient to collect the free charge and move it to the contact. Responsivity values, therefore, show the expected increase with decreasing absorber compensation.

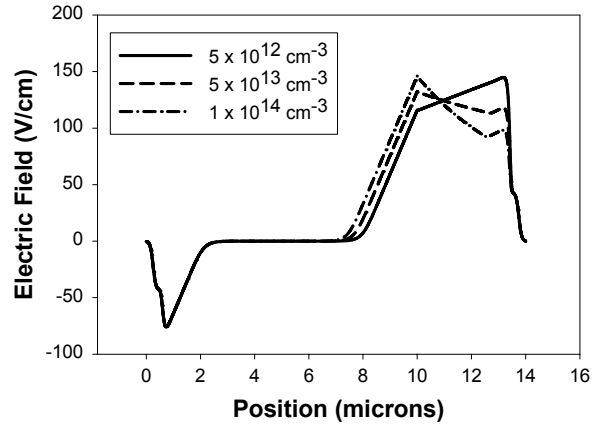
Effect of Variation in Net Blocker Doping

The greater material challenge for BIB development in Ge and/or GaAs is the production of a very high purity blocking layer. Limitations come from the availability of high purity starting materials and from the problems associated with growing a very high purity layer immediately adjacent to much more heavily doped material. Despite some progress, net doping levels below 10^{13} cm^{-3} have not yet been routinely achieved in the development of either Ge or GaAs BIB blocking layers.

Figure 3 shows the field variations produced by varying the blocking layer majority doping from 5×10^{12} to $1 \times 10^{14} \text{ cm}^{-3}$. Minority doping in the layer was fixed at 10^{12} cm^{-3} . The increase in blocker doping causes an increase in the space charge concentration, beginning at the absorber/blocker interface, which leads to a larger electric field gradient. With increased doping, the peak field (for given bias) is increased, as well as the width of the depletion region. One notes that the net space charge in the blocker actually changes polarity over this range of doping. Since the amount of negative space charge (N_A^-) is proportional to the majority N_A doping, the increase in negative space charge shifts the balance from net positive space charge ($N_D^+ > N_A^-$) to net negative space charge ($N_A^- > N_D^+$). This can be seen with plots of spatial variation of the ionized acceptors, donors and free holes⁹.

The results of Figure 3 have generally positive implications for the development of far IR BIBs. The field variations with increasing blocker doping actually lead to larger depletion widths and increased current collection. Even if the bias must be adjusted to avoid breakdown effects, there should be little or no sacrifice in current collection. For doping levels below 10^{14} cm^{-3} , the dark current will be dominated primarily by thermal generation in the absorbing layer, not in the blocking layer. Simulations show that the ratio of photocurrent to dark current is not greatly affected by the blocker doping, since both are generated primarily in the absorbing layer.

Figure 3: Field profiles for Ge:Ga BIB as a function of majority doping in the blocker. $T = 2.5 \text{ K}$. Bias is 50 mV for all cases. $10 \text{ }\mu\text{m}$ absorber and $4 \text{ }\mu\text{m}$ blocking layer. Doping is $2 \times 10^{16} \text{ cm}^{-3}$ in the absorber with a minority doping of $5 \times 10^{12} \text{ cm}^{-3}$.



Effect of interface doping gradient

Finally, we simulate the effect of variations in the doping gradient at the absorber/blocker interface. The sharpness of the interface depends on the ability to change doping levels in the growth system, as well as the diffusion coefficient of the impurities and the growth temperature. While a more gradual drop in doping from absorber to blocker clearly affects the required blocker growth thickness, it would also be expected to have an effect on the field profile and the effective depletion width.

The interface doping gradient is modeled with a hyperbolic tangent function

$$N = N_A + (N_B - N_A) / [1 + \exp((x_0 - x)/a)] \quad (1)$$

where N_A is the absorber doping, N_B is the blocker doping, x is position, x_0 is the interface position and a is a grade parameter that determines the interface spread. A grade parameter of $2 \times 10^{-7} \text{ cm}$ has been used for the simulations of Figures 1-3, representing an almost ideally sharp (spread of less than $0.1 \text{ }\mu\text{m}$) interface.

Figure 4 shows the effect of broadening the interface grade. Doping profiles are shown in Figure 4A and the resultant field profiles, expanded to focus on the interface, in Figure 4B. The blocker thickness has been increased in this series to allow for study of broader gradients. A doping gradient causes a large field gradient at the interface, coupled with a field drop in the blocker and extension of the depletion width into the absorber. This is similar to the behavior observed with increasing blocker doping. In both cases, increased population of majority dopants in the blocker region increases the generation rate, the population of N_A^- and the associated negative space charge.

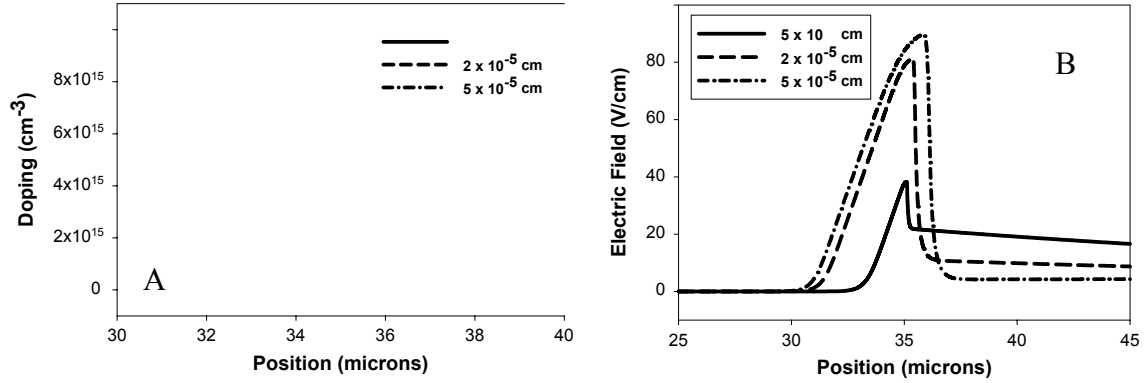


Figure 4: Effect of a doping gradient at the absorber/blocker interface (4A) on field profiles (4B). Simulations were performed for Ge:Sb BIBs¹⁰. A thicker blocking layer is required to simulate broader interface doping profiles.

SUMMARY

A numerical model has been used to illustrate the role of space charge in determining the depletion width and responsivity of BIB detectors. The results indicate that while increased net doping in the blocker and a broader doping gradient at the interface cause a breakdown in the assumption of constant electric field in the blocking layer, the resultant field profiles still provide for collection of photogenerated charge in the absorber and its transport to the collecting contact. In both cases, the development of a field gradient at the interface region actually leads to an increase in depletion width for a given applied bias. The simulations can be used to assist in the growth and characterization of far-IR BIBs. Results suggest that BIB fabrication in Ge and GaAs should be pursued even if the purity levels set by Si BIBs are not immediately attainable.

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